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Initial Operation of the LEDA Beam-Induced Fluorescence Diagnostic[1]

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Abstract. A diagnostic based on beam-induced fluorescence has been developed and used to examine the expanded beam in the High-Energy Beam Transport (HEBT) section of the Low Energy Demonstration Accelerator (LEDA). The system consists of a camera, a gas injector, a spectrometer, and a control system. Gas is injected to provide a medium for the beam to excite, the camera captures the resulting image of the fluorescing gas, and the spectrometer measures the spectrum of the emitted light. EPICS was used to control the camera and acquire and store images. Data analysis is presently being performed offline. A Kodak DCS420m professional CCD camera is the primary component of the optical system. InterScience, Inc. modified the camera with the addition of a gain of 4000 image intensifier, thereby producing an intensified camera with a sensitivity of ~0.5 milli-lux. Light is gathered with a 1" format, 16-160 mm, Computar zoom lens. This lens is attached to the camera via a Century Precision Optics relay lens. Images obtained using only hydrogen from the beam stop exhibited features not yet understood. Images with good signal-to-noise ratio were obtained with the injection of sufficient nitrogen to raise the HEBT pressure to $2\text{-}8 \times 10^{-6}$ torr. Two strong nitrogen lines, believed to be of the first negative group of N_2^+, were identified at 391 and 428 nm.

INTRODUCTION

A prototype beam-induced fluorescence (BIF) profile diagnostic has been constructed and exercised on the HEBT of the Low-Energy Demonstration Accelerator [1], the prototype front end of the Accelerator Production of Tritium (APT) [2]. Such a diagnostic is planned for the low-energy linac of the APT [3]. At low energy, it is expected that the proton beam will interact with the background gas and produce sufficient fluorescence to be observed with an intensified camera. Experiments on the Ground Test Accelerator successfully measured the beam profile using BIF [4]. In those experiments, nitrogen gas was found to produce the best profiles; hydrogen did not work as well. Fluorescent gas profiles are a viable measure of the beam profile if the excited particles do not move far from the point of their

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creation prior to where they de-excite. The purpose of constructing a prototype was to ascertain the feasibility of a fluorescence diagnostic at 6.7 MeV and to identify the mechanisms involved in the production of the fluorescence.

LEDA consists of a 75 keV proton injector, a 6.7 MeV radio-frequency quadrupole (RFQ), a HEBT/beam expander, a suite of diagnostics [5], and a beam stop. At the end of the HEBT, after the beam has been expanded to a nominal 1-cm rms size, it passes a diagnostic cross where both the fluorescence diagnostic and a wire scanner are located. One measure of the success of this diagnostic is how well the BIF profiles compare to those of the wire scanner. Many sets of data, from both diagnostics, were taken to permit a rigorous comparison. On the last day of the experiment, the camera was removed and the spectrometer lens was mounted on the port. Use of the spectrometer allowed identification of the fluorescing nitrogen wavelengths.

The camera was installed on the top port of the six-way cross. A cylinder angling upward at 45° contained the slow wire scanner [6]. Gas was injected into the top of this pipe. An ion gauge was installed on a third member of the cross. Immediately beyond the diagnostic cross was the beam stop. Gas from the beam stop was pumped with the cryopumps attached to a fourth member of the cross. The field-of-view of the camera includes the location where the beam stop gas enters the pumping member of the cross. Some hydrogen is therefore always present in the fluorescing gas.

The gas system was capable of operation in either pulsed or high duty factor modes. All data presented here were taken in a high duty factor mode with HEBT pressures in the range of $2\text{-}8 \times 10^{-6}$ torr. Once the HEBT pressure had been set to the desired level, images or spectra were acquired.

OPTICAL INSTRUMENTATION

Camera

A Kodak DCS420m was chosen for image acquisition. This is a camera, with an easy to use computer interface, mass-produced for the professional photographer. It consists of a Nikon 90s SLR camera with the film back removed and a Kodak camera back substituted. One annoying feature of the Nikon camera body is that it only accepts standard Nikon F-mount lenses. Special interfacing hardware was necessary to attach a remotely controlled lens. The CCD chip used by Kodak has a 1524 by 1012 format with 9-micron pixels.

Kodak provides a dynamic link library for interfacing to the camera. An EPICS PC Input/Output Controller (IOC) running Visual C++ used this library for camera setup, control, and data acquisition. Communication between the camera and the PC were via a fiber optic-extended SCSI link.

Image Intensifier

A DEP XX1450KR image intensifier was incorporated into the camera to provide gain and gating. The DCS420m, with intensifier installed, is a product developed by InterScience, Inc. [7] under contract with NASA.

The intensifier has a 0-1000 V multi-channel plate capable, at full voltage, of providing a gain of 4200 cd/m^2-lux. Camera sensitivity was measured both with and without intensification. The minimal detectable signal level was found to be 460 milli-lux at unity gain and 0.6 milli-lux at maximum gain.

Besides increasing the signal level, the intensifier provides fast, 43 ns, gating. This feature has not yet been used.

The intensifier's photocathode is sensitive from about 360 to 700 nm. Based on the GTA fluorescence experiments, our primary interest was in wavelengths within 20 nm of 400 nm. The system was able to detect the lines of interest.

As quoted by DEP, the intensifier's spatial resolution was 30 line-pairs/mm. Even though degraded by the optical system, this was adequate.

Lenses

Limited access to the tunnel necessitated the use of a remote control lens. The lens chosen was a Computar 16-160mm, f/1.8, zoom lens. As manufactured, the lens has a minimum working distance of 1.5 m. In order to be able to focus on a beam 27.3 cm from the window, and maintain adequate spatial resolution, it was necessary to install 17 mm of extenders behind the lens.

A feature of most remote control lenses, this Computar lens included, is that they are of the C-mount type. Since the Nikon camera body only accepts F-mount lenses, an adapter was necessary. The adapter used in this case was a relay lens system supplied by Century Precision Optics [8]. Two side effects of the relay lens were vignetting and inversion of the image. The former effect resulted in an 8 cm x 5 cm field-of-view at the beam.

Spatial resolution of the entire optical system, CCD included, was measured to be 15 line pairs/mm. This resolution made it possible to resolve 0.1 mm at 27.3 cm.

Spectrometers

Several spectrometers were used. The first was a simple, inexpensive Ocean Optics fiber optic spectrometer. It had dual 11-cm spectrometers with 25-micron slits. The master unit had an 1800 groove/mm grating and was set for 350-545 nm. The slave unit had a 1200 groove/mm grating and was set to view 450-750. At the highest HEBT pressure attempted, 10^{-5} torr, no signal was detected on these systems for integration times up to 45 minutes.

A 0.25-m Jarrell-Ash spectrometer with a Princeton Applied Research Optical Multi-channel Analyzer (OMA) was then used. The detector in the OMA was a model 1420 IR intensified photodiode array with a model 1460 controller. Signals with good signal-to-noise ratios were obtained for integration times of 10 to 30 s. The data presented below were acquired with this system.

Light for all spectrometer experiments was collected with a 60-mm Nikon lens and brought to the control room via 90 m of 600-micron fiber optic cable. Having the spectrometer in the control room greatly facilitated making changes during the experiment.

GAS INJECTION SYSTEM

Gas was injected into the top of the 8-inch diameter stainless cylinder containing the wire scanner. The system consists of a piezoelectric valve driven by a plenum with a controlled pressure. The piezoelectric valve was a Maxtek MV-112 that has a throughput range of 0-6 torr-l/s. The system controlling the backpressure consisted of Balzers components. An RVC-200 was the heart of the system. It is a flow/pressure controller that uses a feedback loop to keep the pressure at the level determined by the user. The RVC-200 adjusts the setpoint on an EVR-116 flow control valve so that the signal from a PKR-250 full-range compact gauge matches the level set by the user. In order to keep feedback loop active, a throttled down 5-liter/minute mechanical diaphragm pump was connected to the plenum.

An ion gauge was attached to a downward directed 8-inch diameter cylindrical member of the diagnostic cross. HEBT pressures quoted below refer to the pressure recorded on this gauge.

Reliable operation of the piezoelectric valve was achieved at a backpressure of 130 torr. Pressures significantly above or below this value either made it difficult to open the valve, or caused it to leak.

Initially, the gas system was designed for pulsed operation. Gas would be injected prior to the macro-pulse to be imaged. Response times, from when the open command was issued until the HEBT pressure reached a maximum, were of the order of 50-200 ms. As it turned out, the timing system was not operational prior to the conclusion of the RFQ characterization experiments. Therefore, the gas injector was operated in a high duty factor mode. Rather than being synchronous with the acceleration of macro pulses, a function generator supplied 1.5 ms wide pulses at 5.45 Hz. These pulses triggered a DEI GRX-1.5k-E high voltage switch. The switch controlled the application of a 0-100 V signal to the piezoelectric valve.

COMPUTER CONTROL

Three computers were involved in operation of the diagnostic. The first was a Motorola 68040 based in a VME crate. It served as an EPICS VME Input/Output Controller (IOC). The VME crate also hosted an Industry Pack carrier containing a DAC, an ADC, a binary input/output module, and a timing system. Through this system we had control of the intensifier gain, gas injector setpoints and feedback, instrument power in the tunnel, and the timing system.

The second computer was a PC IOC interfaced through an extended SCSI link to the camera. It used the Kodak dynamic link library to initialize the camera, take the image, and download the image. Upon demand, the images were stored on this PC.

The final computer was SUN workstation that served as the operator interface. Through EPICS windows, the operator had control of the camera, gas injector, and timing system. Beam profiles were computed from user-selected sections of the image. The user had the capability to select where the section was taken and how many pixels were averaged to produce each point on the profile. Least squares Gaussian fits to the profile were generated by IDL and displayed in the EPICS window.

Implementation of the timing system was not completed in time for use during these experiments. This caused us to operate the gas injection system in the high duty factor mode described above. In addition, the camera was operated under software control. The shutter opened asynchronously from the macro-pulse structure of the beam and stayed open for 0.77 s.

DATA

Initial data were taken with no added nitrogen. During cw beam operation at 100 mA, the HEBT pressure due to hydrogen from the beam stop was typically 2-4x10^{-6} torr. Figure 1 shows an image typical of hydrogen fluorescence. The beam direction is from top to bottom. The image consists of a circular feature, out of the top of which extends something that moved as the beam was steered. At the present time we have no explanation to offer as to the presence of the circular feature. This location coincides with the location of the pipe leading to the HEBT vacuum pumps.

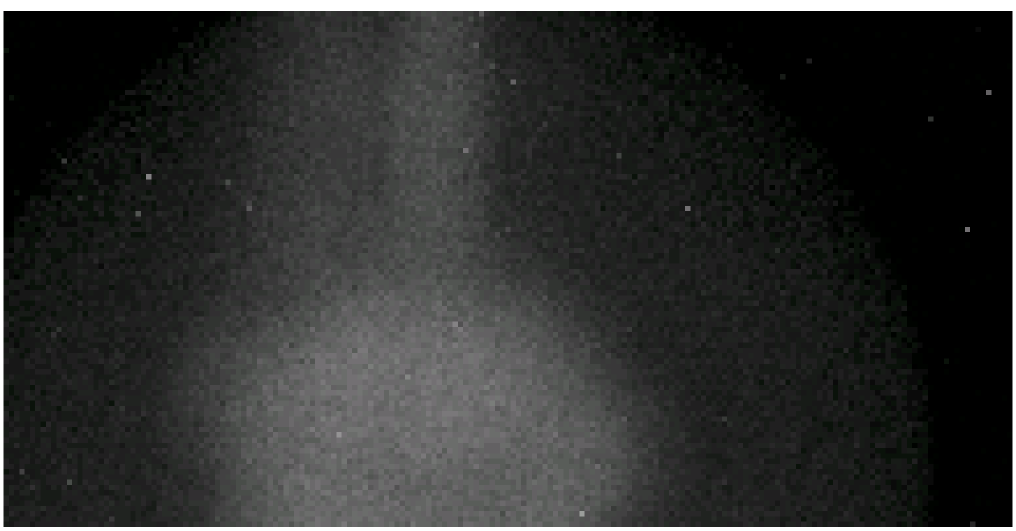

FIGURE 1. Image in 2.6x10^{-6} torr of hydrogen, intensifier gain = 320, 95 mA cw beam operation.

Images taken where the nitrogen pressure dominates that of hydrogen were uniform in the axial direction. All profiles described below were obtained under such conditions.

Preliminary comparisons have been made of profiles measured by both BIF and by the wire scanner. BIF data were taken with 90 mA through the RFQ, 20 ms pulses at 5 Hz, and a total pressure of 2.65×10^{-6} torr in the HEBT, of which 9×10^{-8} torr was hydrogen. Wire scanner data were also taken at 5 Hz, but the pulse length was 900 μs. BIF data were taken with the beam steered approximately 3 cm to the right of center and 3 cm to the left. The pulse length was then reduced, and wire scanner data were taken for the same steering magnet setpoints.

Figure 2 shows the BIF data for this comparison. Both profiles were fit to a Gaussian, which is also displayed. Vignetting of the profile occurs for pixels ~1300 and beyond. These were not included in the fit. Both profiles have rms widths of 11.7 mm and their centroids are separated by 5.6 cm. By way of comparison, Gaussian fits to the wire scanner data yield rms widths of 10.5 mm and a centroid shift of 6.5 cm due to the steering. This agreement, within 10 to 15%, is very encouraging, albeit preliminary. More detailed analysis, including comparison of the moments of the distributions, remains to be carried out.

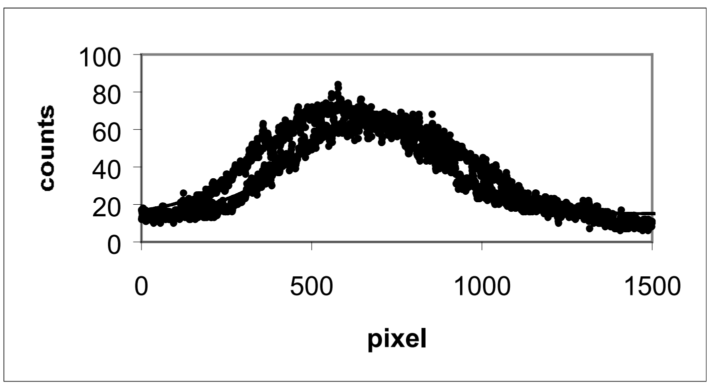

FIGURE 2. BIF data taken with 20 ms pulses at 5 Hz at a nitrogen pressure in the HEBT of 2.6×10^{-6} torr. Both the raw data and Gaussian least square fits are indicated.

Additional data were taken at different beam sizes, both larger and smaller than the nominal size analyzed above. Still more data were taken at various HEBT pressures and intensifier gains. This was done in an effort to quantify the light emission. This data remains to be analyzed.

Difficulty was experienced in trying to measure profiles of a cw beam. As mentioned previously, profiles dominated by hydrogen from the beam stop exhibited features that did not correspond to the beam. Cw operation resulted in HEBT hydrogen pressures of $\sim 4 \times 10^{-6}$ torr. With a limit of $\sim 2 \times 10^{-5}$ before vacuum interlocks shutdown the vacuum system, it was not possible to eliminate the hydrogen features from the profile under cw conditions. When the duty factor was reduced to 60%, the hydrogen pressure decreased by an order of magnitude. Under such conditions, the hydrogen pressure could be made to be 5% or less of the total pressure and trustworthy profiles obtained.

Spectrometer data were taken at 70% duty factor, with 1×10^{-6} torr of hydrogen partial pressure out of a total pressure of 6×10^{-6} torr. Figure 3 shows the data resulting from a 30-s integration. The means of the two lines were 390 and 426 nm, with standard deviations of 3.1 and 3.5 nm, respectively. Experiments involving the excitation of nitrogen by energetic protons carried out in the late 50's and early 60's showed strong emission from the first negative system of N_2^+ [9, 10]. The strongest lines in this system are 390.1, 427.8, and 470.9 nm. We have evidence here for the first two.

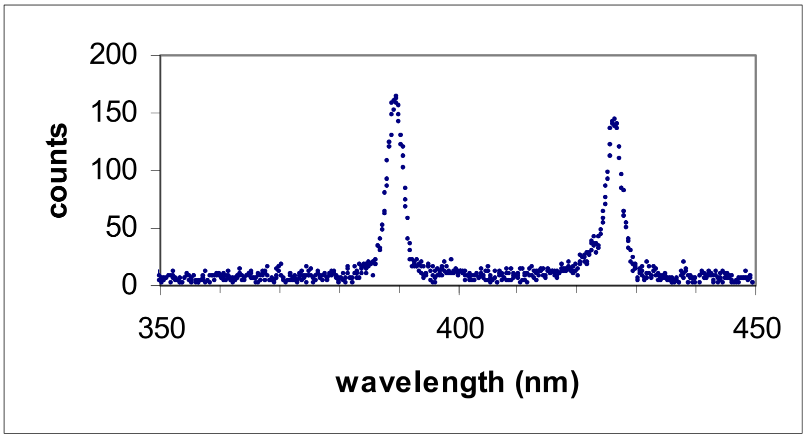

FIGURE 3. Spectrum obtained using the 0.25-m Jarrell-Ash spectrometer equipped with an OMA detection system during a 30-s integration.

These two lines are the strongest of the (0, n) sequence. Evidence of the third line, the (0, 2) transition, is shown in figure 4. The data in this figure were obtained when the 600-groove/mm grating used in figure 3 was rotated to view slightly longer wavelengths. Neither Hα nor Hβ was observed during the use of either the 600 or 150 groove/mm gratings.

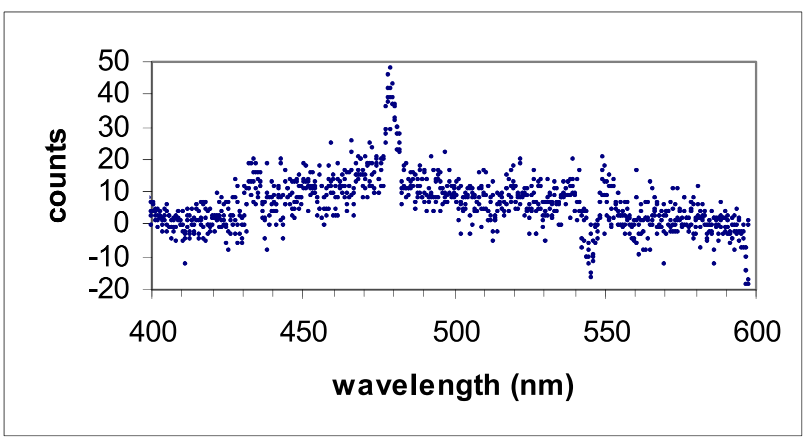

FIGURE 4. Spectrum obtained using the 0.25-m Jarrell-Ash spectrometer equipped with an OMA detection system during a 10-s integration.

CONCLUSIONS

We have demonstrated that there is sufficient background gas fluorescence taking place with a 6.7 MeV proton beam to measure beam profiles. Evidence suggests that the lines of nitrogen that are causing the fluorescence are those of the first negative system of N_2^+. The possibility that the lines are atomic is still under consideration. It was possible to measure profiles with 1 ms length macro-pulses at a 10 Hz rep rate. With the shutter open for 0.77 s, the image is the sum of 7 macro-pulses. This implies that the system's level of detectability is a single macro-pulse of 5-7 ms length, at 100 mA, and nominal 1-cm rms width.

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